The possible feature of the energy spectrum of the primary cosmic rays at ultra-high energies

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***Abstract*. The energies of the most energetic extensive air showers observed at the Yakutsk array have been estimated with help of the all detectors readings instead of using of the standard procedure with a parameter $s(600)$. These detector readings have been compared with the detector responses, calculated for all particles which hit the scintillation detectors in each individual shower with observed the zenith and azimuth angles with help of the GEANT4 code. In turn the code CORSICA-6.616 have been used to produce such particles in the atmosphere in these individual showers and propagate them to detectors at the level of observation. Calculations have been carried out in terms of the QGSJET-2 and Gheisha-2002 models with the thinning parameter 10^{-8} for the primary protons and helium, oxygen and iron nuclei. The energy of the most energetic extensive air shower observed at the Yakutsk array happened to be 200, 200, 180 and 165 EeV with the values of the χ^2 function per one degree of freedom 0.9, 1., 0.9 and 1.1 for the primary protons and helium, oxygen and iron nuclei accordingly. Thus interpreting data in terms of the QGSJET-2 and Gheisha 2002 models we conclude that after the bump and decreasing of the flux of the primary particles due to the Greisen, Zatsepin and Kuzmin effect that has been observed at the HiRes array and at the Pierre Auger observatory there is a possible feature in the energy spectrum – some increase in the flux at energies 200 – 300 EeV observed both at the Yakutsk array and at the AGASA array. Such possible feature may be understood as the flux of heavy primary nuclei. It is also not excluded that some new component of the spectrum is observed or the Lorentz invariance may be violated at such huge energies. As an alternative conclusion the models QGSJET-2 and Gheisha 2002 should be changed so as to produce much more muons in a shower.**

***Keywords*: extensive air shower**

I. INTRODUCTION

The energy of extensive air showers (EAS) observed at the Yakutsk array (YA) is usually estimated as follows. First, for each individual shower the zenith and azimuth angles and coordinates of axis are determined. Then the signal $s(600)$ is estimated from all scintillation detector readings. This signal is determined by the energy deposited in a detector at a distance of 600 m from the shower core by all shower particles (by electrons, positrons, gammas and muons). Then this signal is recalculated to the value it would have in the vertical shower with the help of the average value of the attenuation length $< \lambda >$ which is estimated by applying the constant integral intensity cut method [1]. The calculated zenith-angle dependence is also may be used but with average value of the attenuation length $< \lambda >$. But such procedure leads to large uncertainties in energy estimate for the individual showers. First, in terms of model calculation it was shown that the values of the attenuation length $< \lambda >$ estimated with the help of such procedure and calculated for the average shower development differ considerably [2], [3]. Second, and it is a main source of uncertainty, the individual showers may be generated by varies species of the primary particles. Besides, the real value of the attenuation length λ in individual vertical showers may differ from ~ 200 up to $\sim 2000\ g \cdot cm^{-2}$ [4] due to fluctuations in the longitudinal development. Indeed, the steepness of the individual cascade curve at the level of observation (and the attenuation length λ) may vary very considerably due to fluctuations in the points of first and subsequent interactions of the primary particle with atomic nuclei in the atmocphere. Thus, the uncertainty of the signal $s(600)$ estimated for the vertical showers with the help of a factor such as $\exp(-\Delta x/\lambda)$ may be very large, where Δx is a slant depth. At last, the energy E is estimated with help of the following formula

$$E = 4.8 \cdot 10^{17} \cdot s(600),\ eV. \tag{1}$$

In the formula (1) uncertainties are missed for simplicity and it was suggested that the signal $s(600)$ is proportional to the energy E of a shower. This formula is based on the calibration of signals with help of the Vavilov-Cherenkov radiation of a shower. Again, this calibration has been carried out for the average value of a signal from some sample of showers. For the individual vertical showers the numerical coefficient in

(1) should vary due to fluctuations. Besides, it should be mentioned that in terms of the model calculation the value of this numerical coefficient was estimated as being 1.6 – 1.7 times less than quoted in (1) [5]. Thus, any alternative methods of energy estimation are of interest. It was suggested that readings of all detectors should be compared with calculated signals for a shower with the given values of the zenith and azimuth angles [6]. Calculations have been carried out for the giant shower observed at the YA [7] on the base of the original code. It was assumed in accordance with experimental data that this shower consist mainly of muons and their deflections in the geomagnetic field have been taken into account. The energy of this shower has been estimated as $\sim 3 \cdot 10^{20}$ eV. In this paper calculations of signals for this giant shower at many points with different distances from the shower core have been carried out for some sample of the individual showers induced by various primary particles to take into account fluctuations in the longitudinal and lateral development. Then the χ^2 method has been used to find out which of calculated individual showers agree best with data [7]. As new energy estimate are happened to be rather high some analyses of energy spectra observed at various arrays have been carried out and the new interpretation of the energy spectrum has been suggested at ultra high energy region with the possible variable contribution from the local sources.

II. METHOD OF SIMULATIONS

Simulations of the individual shower development in the atmosphere have been carried out with the help of code CORSIKA-6.616 [8] in terms of the models QGSJET2 [9] and Gheisha 2002 [10] with the weight parameter $\epsilon = 10^{-8}$ (thinning). The program GEANT4 [11] has been used to estimate signals in the scintillation detectors from electrons, positrons, gammas and muons. The bank of detector responces has been calculated for electrons, positrons and gammas with energies in the interval 0.001–10 GeV and muons with energies in the interval 0.3–1000 GeV which hit a detector at various the zenith angles (from 0^o up to 60^o). This bank of detector responces was used to estimate a signal in the scintillation detector when a shower particle hits it. The total area of $5 \times 5\ km^2$ in the detector plane was divided into 201×201 squares with the side of 25 m. With the help of the code CORSIKA-6.616 the spread of shower particles in the detector plane has been estimated and the bank of detector responces has been used to calculate the signals in each square, regarded as a detector. Thus, the matrix of 201×201 detector responces for each individual shower has been calculated. These matrixes of detector responces were calculated for individual showers with the same energy 10^{20} eV. Calculations have been carried out for four species of the primary particles (protons and nuclei of helium, oxygen and iron) with a statistics of four individual events for every species of the primaries. Readings of the 31 scintillation detectors have been used to search for the minimum of the function χ^2 in the square with the width of 400 m and a center determined by data with a step of 1 m. These readings have been compared with calculated responces which were multiplied by the coefficient C. This coefficient changed from 0.1 up to 4.5 with a step of 0.1. Thus, it was assumed, that the energy of a shower and signals in the scintillation detectors are proportional to each other in some small interval. New estimates of energy, coordinates of axis and values of the function χ^2 have been obtained for each individual shower.

The analysis of the energy spectra observed at various arrays has been carried out in the following way. The base universal spectrum $J_b(E) = A \cdot E^{-3.25}$ has been suggested mainly on assumption of data [12] at energies above 10^{17} eV with $A \approx 7.1 \cdot 10^{28}\ m^{-2} s^{-1} sr^{-1} eV^{2.25}$. All possible features of the energy spectrum of the primary particles are considered relatively to this spectrum. Besides, the reference spectrum $J_r(E)$ has been suggested as follows. For the energy we will use besides E (in eV) additional notation $y = \lg(E/1\ eV)$. In four energy intervals (i=1, 2, 3 and 4) $17. < y < 18.65$, $18.65 < y < 19.75$, $19.75 < y < 20.01$ and $y > 20.01$ the spectrum $J_r(E)$ has been approximated by the following exponent functions

$$J_1(E) = A \cdot E^{-3.25},$$
$$J_2(E) = C \cdot E^{-2.81},$$
$$J_3(E) = D \cdot E^{-5.1},$$
$$J_4(E) = J_1(E) = A \cdot E^{-3.25}$$

accordingly. Constants C and D may be expressed through A and equations for $J_r(E)$ at the boundary points. For these four intervals we assume the reference spectrum as

$$\lg z_i = \lg(J_i(E)/J_1(E)),$$

where i=1, 2, 3, 4. This reference spectrum is then represented as follows

$$\lg z_1 = 0,$$
$$\lg z_2 = 0.44 \cdot (y - 18.65),$$
$$\lg z_3 = 0.484 - 1.85 \cdot (y - 19.75),$$
$$\lg z_4 = 0$$

accordingly. We consider the spectrum $J_b(E) = A \cdot E^{-3.25}$ as universal up to highest energies. The first feature of the spectrum is suggested to be considered as some excess at energies $18.65 \le y \le 20.01$. The left side of this exess is approximated as $J_2(E) - J_1(E)$ while the right side as $J_3(E) - J_1(E)$. The possible second feature at energies (2–3)$\cdot 10^{20}$ eV will also be discussed. Results of the spectra $J(E)$ observed at various arrays have been expressed as

$$\lg z = \lg(J(E)/J_1(E))$$

and are shown in comparison with the reference spectrum.

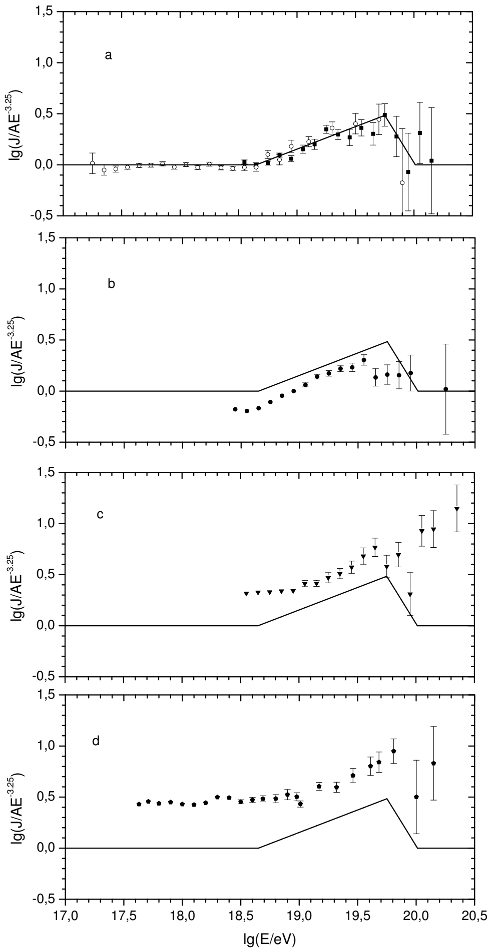

Fig. 1: The energy spectra observed at various arrays and the reference spectrum (solid line): a) – [12], (b) – [16], (c) – [13], (d) – [17]

III. RESULTS OF ENERGY ESTIMATIONS AND ANALYSIS OF THE ENERGY SPECTRUM

The 16 various values of energy estimates for 16 individual simulated showers with different values of the function χ^2 have been obtained for the same sample of the 31 experimental readings of the observed giant shower [7]. As the giant shower is very inclined muons make main contribution to signals in the scintillation detectors. The energy estimates are minimal and change inside the interval (1.6–1.75)$\cdot 10^{20}$ eV with the value ~ 1.1 of the χ^2 function per one degree of freedom for the iron nuclei primaries which produce more muons than the proton primaries . For the proton and helium nuclei primaries energy estimates are maximal and change inside the interval (1.8–2.4)$\cdot 10^{20}$ eV with the value ~ 0.9 of the χ^2 function per one degree of freedom. For the oxygen nuclei primaries the energy estimates are in the interval (1.8–2)$\cdot 10^{20}$ eV which is between intervals for proton and iron nuclei primaries. It should be mentioned that only muons contribute $\sim 80\%$ of the total signal and therefore energy estimate increases up to $2.8 \cdot 10^{20}$ eV for the proton primaries if only muons are taken into account as in [7] disregarding the contribution of electrons, positrons and gammas. New coordinates of shower axis vary from the experimental one by some dozen of meters. So we can make main conclusion that in terms of the QGSJET2 [9] and Gheisha 2002 [10] models and the proton primaries there are extensive air showers with energies $\sim 2 \cdot 10^{20}$ eV. This estimate may be decreased up to $\sim 1 \cdot 10^{20}$ eV only in terms of some new model which produces twice as much muons as [9] and [10]. It is not easy because muons are produced in low energy region where the physics of interactions is known. But the energy estimate decreases up to $\sim 1.6 \cdot 10^{20}$ eV for the iron nuclei as the primary particles. It should be remind that such giant showers have been also observed in [13]. It looks as a some contradiction to the suggestion by Greisen, Zatsepin and Kuzmin (GZK) [14], [15]. Just on the contrary, the observations [12], [16] show no giant showers in accordance with the GZK prediction but not with data [13], [17]. It is evidently that all world data should be understood. Of course, some uncertainties in energy estimates may exist.

But it is also worth-while, to consider some new idea about the energy spectrum at ultra high energies. Usually, this spectrum is considered as universal and stationary [18]. It is possible if many uniformly distributed sources contribute to the spectrum. In case of the near-by sources [19] distributed anisotropic-ally their contribution to the different intervals of the spectrum may be variable. If a power of local sources is not high one source may give a contribution to the number of observed events only once in many years. So, various sources may contribute to the spectrum at different time of an exposure. Due to deflection in magnetic fields arrival directions of showers differ from directions to local sources. If the number of sources is not high their contribution to the spectrum would be very variable and even chaotic. The primary particles from such local sources may be considered as some variable excess above the suggested universal spectrum $J_b(E)$. Decreasing of the flux of the primary particles due to the GZK effect should probably be considered relatively to this universal spectrum but not relatively the observed bump as in [12], [16]. Evidently, it is a difficult problem. Of course, the flux of particles at exess energies is also supressed by the GZK effect. Fig. 1 illustrates our suggestion. Data $\lg z = \lg(J(E)/J_1(E))$ observed at various arrays are shown in Fig. 1 as follows: (a) – [12] (open circles – HiRes2, solid circles – HiRes1), (b) – [16] (solid circles), (c) – [13] (solid triangles) and (d) – [17] (solid pentagons). The reference spectrum is also shown on all Figures. As it was expected the data [12] agree very well with the reference spectrum. The data [16] are below this reference spectrum, and the data [13]

and [17] are much above it. What possible features are seen in Fig. 1? First, no predicted dip [18] at energy 10^{18} eV is seen. Just the contrary is true: in this energy region the exponents of all spectra are approximately the same with a good accuracy. Second, all data show some excess in the energy interval (5–10)$\cdot 10^{19}$ eV (so called "bump" [18]) which may be considered as a contribution from the local sources. The observation of the anisotropy of arrival directions of showers [16], [19] supports this statement. At last, no dramatic fall of the flux of the primary particles relatively to the reference spectrum is seen at energies above 10^{20} eV. Indeed, due to [12] the number of expected events with energies above $6.3 \cdot 10^{19}$ eV is equal to 43.2 but only 13 events were observed. According to the reference spectrum the number of expected events is calculated as 16 that with the Poisson fluctuation taken into account agrees with the observed number. Due to [16] numbers of expected events with energies above $6 \cdot 10^{19}$ eV and 10^{20} eV are equal to 167 and 35 accordingly while only 69 and 1 events were observed. The reference spectrum gives 137 and 7 events accordingly. The disagreement decreased but not vanished. This fall may be regarded as the observation of the GZK supression of the flux of the primary particles. It may be commented that data [16] include two empty bins which should contain 6 events. The Poisson probability that no one was observed equals to $\sim 2.5 \cdot 10^{-3}$. It should also be mentioned that the intensity of the reference spectrum is ~ 1.5 times higher than used in [16]. Besides, some uncertainties in energy estimates are possible as we believe due to the constant integral intensity cut method [1] which disregarded fluctuations. The data [13] illustrate possibly a contribution of local variable sources at energies above 10^{20} eV while some uncertainties in energy estimates or aperture may be of importance at energies below $5 \cdot 10^{19}$ eV. The same comments may be addressed to data [17] with additional remark that calculated energy estimate is 1.6 times less than used in data. Besides, data [13], [17] show probably the second variable excess at energies (2–3)$\cdot 10^{20}$ eV. This second variable exess may be regarded as a contribution of heavy nuclei to the flux of the primary particles from the local sources. It is also not excluded that the Lorentz invariance may be violated at such huge energies [20], [21], [22]. The intensity of local sources on the Earth may be estimated as integral on differences $J_2 - J_1$ and $J_3 - J_1$ accordingly in case of the first exess. This integral is estimated as $I \approx 4 \cdot 10^{-14}\ m^{-2}s^{-1}sr^{-1}$. If we assume a distance to local sources as $R \sim 30$ Mpc, a typical energy $E \sim 10^{19}$ eV and an angle of emission as ~ 1 sr then we obtain the power of all local sources as $3 \cdot 10^{33}$ W which is in agreement with estimates in [23], [24].

IV. Conclusion

The new method has been suggested to estimate energy of extensive air showers by comparison all detector readings with calculated signals for a sample of individual events induced by various primary particles. Simulations of the individual shower development in the atmosphere have been carried out with the help of code CORSIKA-6.616 [8] in terms of the models QGSJET2 [9] and Gheisha 2002 [10] with the weight parameter $\epsilon = 10^{-8}$ (thinning). The program GEANT4 [11] has been used to estimate signals in the scintillation detectors from electrons, positrons, gammas and muons. New estimates of energy of the giant air shower observed at YA [7] have been calculated in terms of the QGSJET2 [9] and Gheisha 2002 [10] models as $E \sim 2 \cdot 10^{20}$ eV for the proton primaries and $E \sim 1.7 \cdot 10^{20}$ eV for the primary iron nuclei. The base universal spectrum such as $J_b = A \cdot E^{-3.25}$ have been suggested at energies above 10^{17} eV. It was also suggested that some possible local sources may produce variable contribution to the different regions of the energy spectrum at super high energies. The fall of the flux of the primary particles due to the GZK effect should be considered relatively the some base spectrum. Possibly, the second exess at energies (2–3)$\cdot 10^{20}$ eV has been observed in [13], [17].

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